(54) Title: LOW COMPLEXITY BEAMFORMERS FOR MULTIPLE TRANSMIT AND RECEIVE ANTENNAS

FOUR TRANSMIT ANTENNAS,
TWO RECEIVE ANTENNAS, R=4 bits/sec/Hz
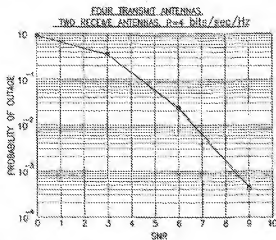
→ SPATIAL WATER-FILLING WITH PERFECT CSIT
→ POWER ALLOCATION QUANTIZED TO 2 BITS

(57) Abstract: Beamforming systems having a few bits of channel state information fed back to the transmitter benefit from low complexity decoding structures and performances gains compared with systems that do not have channel state feedback. Both unit rank and higher rank systems are implemented. Substantial design effort may be avoided by following a method of using functions formulated for space-time systems with the change that the channel coherence time is equated to the number of transmit antennas and the number of antennas in the space-time formulation is fixed at one.

WO 2004/040690 A2

Low Complexity Beamformers for Multiple Transmit and Receive Antennas

TECHNICAL FIELD

The field of the invention is telecommunications, in particular antenna systems for cellular systems.

BACKGROUND OF THE INVENTION

Various beamforming schemes for wireless systems equipped with multiple transmit and multiple receive antennas are known in the art. At present, space time coding schemes are currently proposed for multiple antenna systems.

Figure 1, taken from US Patent 6,584,302, assigned to the assignee hereof, presents a transceiver that has a group of antenna elements 200-204 for transmitting and receiving. The transceiver is usually a base station but it can also be a subscriber equipment. The antenna with several elements can be an antenna array or some other kind of cluster of antenna elements. Referring to receiver 260, each signal received from each antenna 200-204 enters RF-means 206-210 that convert the radio frequency signal to baseband signals in a known manner. The signals are digitized in A/D-converters 212-216. The digital baseband signals are multiplied by coefficients W_1 -W_M that form the shape of the beam of the antenna in multipliers 218-222. The coefficients W_1 -W_M are digital complex numbers. The receiver searches for the values of the coefficients W_1 -W_M that produce the best reception. Antenna responses are calculated in an antenna response unit 224 for each antenna element. The antenna responses are ranked and a subset of the set of the antenna responses is selected in rank and select unit 226.

A response of an antenna element is similar to an impulse response and is calculated

1   by using correlation. In the correlation a known pseudo-random spreading code is

2   correlated with the received signal L times. L is the number of paths of the multipath

3   propagated signal. After calculating one correlation value the spreading code is

4   shifted by a time difference ΔT, which can be the same as the duration of a chip.

5

6   In the transmitter 262 the subset comprising at least one antenna response is fed to a

7   coefficient unit 230 that calculates the coefficients a_1 -a_M for each antenna element

8   200-204 transmitting a signal. The signal to be transmitted is multiplied by the

9   coefficients using the multipliers 232-236. The signal weighted by the coefficients a_1

10   -a_M is then converted to an analog signal by D/A-converters 238-242. After that, the

11   analog signals are converted to radio frequency signals in RF-means 244-248 and the

12   radio frequency signals are transmitted by the antenna elements 200-204.

13

14   Low receiver complexity is one of the important design goals for downlink

15   transmission where the handset (receiver) is constrained in its computational

16   abilities.

17

18   It is well known that channel state information at the transmitter can enhance the

19   system performance significantly. However, in practical systems, only partial

20   channel information may be available at the transmitter due to the limited nature of

21   the feedback resources

22

23   Hence, it is important to design feedback based transmission schemes for the cases

24   where partial channel information is available at the transmitter. Transmission

25   schemes for single receive antenna systems utilizing quantized channel information

26   have been developed, but are not satisfactory.

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28
29   SUMMARY OF THE INVENTION
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2

The invention relates to a design criterion and beamformer constructions, which make use of finite rate feedback in the system.

A feature of the invention is a beamforming scheme for wireless systems equipped with multiple transmit and multiple receive antennas.

Another feature of the invention is the use of mathematical formalism originally developed for unitary space-time constellations for a beamformer.

Another feature of the invention is the application of a beamformer construction that is equivalent to a spatial water-filling solution.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 illustrates in block diagram form a multiple antenna system according to the prior art.

Figures 2 - 6 illustrate performance of various configurations.

BEST MODE OF CARRYING OUT THE INVENTION

The beamforming schemes presented in this disclosure result in improved performance at provably lower computational complexity compared to the space time coding schemes currently proposed for multiple antenna systems. Low receiver complexity is one of the important design goals for downlink transmission where the handset (receiver) is constrained in its computational abilities.

It is well known that channel state information at the transmitter can enhance the system performance significantly. However, in practical systems, only partial channel information may be available at the transmitter due to the limited nature of the feedback resources. Hence, it is important to design feedback based transmission

3

1 schemes for the cases where partial channel information is available at the

2 transmitter. Transmission schemes for single receive antenna systems utilizing

3 quantized channel information have been developed.

4 In this work, we present a design criterion and beamformer constructions which

5 make use of finite rate feedback in the system. In the first part of this disclosure, we

6 present a unit rank beamforming strategy for multiple transmit and multiple receive

7 antenna systems. In the second part, we present an algorithm to extend the

8 beamformer codebook constructions to mimic a spatial water-filling solution with a

9 finite number of feedback bits. We will show that both the schemes result in better

10 performance at lower decoding complexity compared to space time coding. In

11 particular, we can show that unit rank beamforming schemes are useful when the

12 transmission rate is small. In fact, we can show that the unit rank beamforming

13 schemes result in significant performance gains over space time coding schemes

14 when $2^{R/t}/t < 1$, where R is the rate of transmission in bits/sec/Hz, r is the number of

15 receive antennas and t is the number of transmit antennas. When this condition for

16 unit rank beamforming is not met, i.e., for higher transmission rates, we propose

17 higher rank beamforming schemes based on the spatial water-filling algorithm, using

18 finite rate feedback.

19

20 Consider a multiple antenna system with t transmit antennas and r receive antennas,

21 such as that illustrated in Figure 1. Let us suppose that we wish to transmit at a

22 spectral efficiency of R bits/sec/Hz. We denote the t x 1 transmitted vector by X

23 while the r x 1 received vector is denoted by Y. The additive white noise vector is

24 denoted by N while the frequency non-selective Rayleigh fading channel between

25 the transmit antennas and the receive antennas is given by the

26 r x t matrix H. With this notation, the received signal Y can be expressed as

  $Y = HX + N.$ (1)

27

28

1   The channel fading is assumed to be quasi-static over time; i.e., the channel remains

2   constant within a frame while the channel realization is independent from frame to

3   frame. We assume that the channel is known perfectly at the receiver. In practice,

4   good channel estimates can be obtained at the receiver by employing preamble based

5   training in the system. We also assume the existence of an error-free feedback

6   channel from the receiver to the transmitter which carries B bits every frame. For

7   simplicity, power adjustment over time; (i.e., temporal power control) is not

8   performed.

9

10   We will first discuss unit rank beamforming schemes and analyze their performance.

11   Unit rank beamforming schemes are optimal in the sense of minimizing outage

12   probability in the important case when the number of receive antennas is restricted to

13   1. Further, we have shown that unit rank beamforming with multiple receive

14   antennas is optimal in the sense of minimizing the pair-wise codeword error

15   probability. Additionally, unit rank beamforming schemes result in simple decoding

16   structures with low computational complexity.

17

18   We have shown that transmission along the dominant eigenvector of the channel

19   minimizes the pairwise codeword error probability in the system. It has also been

20   shown that the transmission along the dominant eigenvector of the channel

21   maximizes received SNR while resulting in maximum diversity. We refer to this

22   transmission strategy as the unit rank beamforming scheme.

23

24   It is an advantageous feature of the invention that the decoding complexity of the

25   unit rank beamforming scheme is independent of the number of transmit antennas.

26   Since there is a single stream of data (corresponding to the eigen channel with the

27   best eigen value) the resulting encoder is a scalar encoder and hence independent of

28   the number of transmit antennas. As a result, the corresponding decoder is also a

29   scalar decoder and hence the decoding complexity is independent of the number of

30   the transmit antennas. In contrast, space time codes encode across all the transmit

5

1   antennas in a joint fashion, thus resulting in a vector encoder whose order is given by

2   the number of transmit antennas. In such a case, the corresponding vector decoder's

3   complexity is exponential in the number of transmit antennas.

4   Consider the example of a finite size beamformer codebook given by $C = \{C_1, C_2, \cdots$

5    $C_N \}$. We can show that the quantizer which minimizes the outage probability is

6   given by

$$\min_{C_i \in C} \| H C_i^\dagger \|_2^2, \tag{2}$$

7

8   where $\|.\|_2$ represents the l_2 norm on $\mathbb{C}^t$. Hence, a given channel realization H will

9   be mapped to the beamforming vector C_i which minimizes expression (2). It can also

10   be shown that as N gets large, the quantization rule given by (2) leads to the

11   dominant eigenvector of the channel. This follows from the Rayleigh quotient, which

12   states that $\|HV\|_2$ is maximized when V is the dominant eigenvector of $H^\dagger H$.

13

14   We can further establish a lower bound on the outage performance of the unit rank

15   beamforming scheme when the beamforming codebook size is constrained to $N=2^B$

16   vectors. In particular, for t transmit antennas and r=2 receive antennas, we can show

17   that the outage probability of the system is bounded below as follows:

18

$$P_{out}(R,P) \geq 1 - N(1+\gamma_0)e^{-\gamma_0} + e^{-\gamma_1} \left(\sum_{k=0}^{2t-1} \frac{N(1+\gamma_0)(\gamma_1 - \gamma_0)^k - \gamma_1^k}{k!} \right)$$

$$- N e^{-\gamma_1} \gamma_0 \frac{(\gamma_1 - \gamma_0)^{2t-1}}{(2t-1)!} \tag{3}$$

19

20

1   Where $\gamma_0 = \frac{2^R - 1}{P}$ and γ_t is a function of N, t and γ_0.

2   Hence, with the above quantization rule, all the beamformer constructions which

3   were known for a single receive antenna can be adapted for multiple receive

4   antennas also. The design criterion for good beamformer codebooks in the case of

5   single receive antenna is therefore given by

$$\min_{\mathcal{C}} \ \max_{i, j; i \neq j} |\langle C_i, C_j \rangle|. \qquad (4)$$

6

7

8   Under appropriate circumstances, the above design criterion is mathematically

9   equivalent to the design criterion of unitary space time constellations for non-

10   coherent constellations. Hence, all the constructions available for unitary

11   constellation design can also be used for the beamformer design problem with the

12   quantization metric given by (2).

13   Figure 2 shows the performance of the quantized unit rank beamformers with four

14   transmit antennas and two receive antennas transmitting at R=2 bits/sec/Hz (curves

15   104 and 106). The performances of a space-time coding scheme which does not use

16   any channel state information (curve 110) as well as the spatial water-filling solution

17   which requires complete channel state information (curve 102) are also given for

18   comparison. With 6 bits of feedback information (curve 106), we see a gain of over

19   2.5 dB for the unit rank beamforming scheme over the space time coding scheme at

20   an outage performance of 10^{-2}. The gains increase further as the number of feedback

21   bits is increased. Note that we can potentially gain up to 4dB over space time codes

22   using unit rank beamforming schemes. Further, the gap between the unit rank

23   beamforming scheme (curve 104) and the higher rank water-filling scheme (curve

24   102) is less than 0.4dB for this rate of transmission. The performance gains are in

25   addition to significant reduction in complexity for the beamforming scheme over the

26   space time coding as already explained. Further, the performance of dominant

7

1   eigenvector beamforming (curve 104) which is the limit of the unit rank

2   beamforming as the number of beamforming vectors gets large is also given in

3   Figure 2.

4   In the next section, we will present higher rank beamforming schemes (spatial water-

5   filling) with finite rate feedback, which provide significant performance gains over

6   space time codes as well as unit rank beamforming schemes when the transmission

7   rate is increased (in particular, when $2^{R/t}/t < 1$, where R is the rate of transmission, r

8   is the number of receive antennas and t is the number of transmit antennas).

9

10   We now propose an algorithm to extend the unit rank beamforming approach for

11   multiple receive antennas to a quantized spatial water-filling approach for the case of

12   two receive antennas. The algorithm can be easily extended to the case of more than

13   two receive antennas. Next generation handsets are expected to be equipped with no

14   more than two antennas, due to size and cost constraints. Hence, the case of two

15   receive antennas is important for downlink transmission in cellular systems.

16

17   For the case of a spatial water-filling solution, the transmitter needs to possess

18   information about the eigenvectors as well as the eigenvalues of $H^{\dagger}H$. Note that

19   the knowledge of the relative value of the eigenvalues (e.g. ratio of the eigenvalues)

20   will not suffice for the water-filling power allocation. The invention employs a

21   quantizer solution in which the eigenvectors and the power allocation vector are

22   quantized independently. This separation imposes certain structure on the quantizer

23   design, which advantageously reduces the complexity of implementation of the

24   quantizer in practice.

25   In the case of two receive antennas (r = 2), $H^{\dagger}H$ can at most have two non-zero

26   eigenvalues. Hence, the knowledge at the transmitter should comprise these two

27   eigenvectors (corresponding to non-zero eigenvalues) as well as the corresponding

28   eigenvalues. The inventors have realized that significant savings in feedback

8

1   resources can be obtained if the power allocation is made at the receiver and the

2   information about the power distribution in the two eigen channels is passed back to

3   the transmitter. Further, there is no loss in information if the power distribution

4   vector P_1, P_2 is normalized to unity since the total power available (P) is known at

5   the transmitter. Hence, we can design a computationally simple quantizer for the

6   power allocation vector. Further, we have observed that a 2 bit quantizer effectively

7   conveys all the information required for the power allocation at the transmitter.

8   Additionally, we can gain up to one bit in feedback resources by noting that P_1

9   corresponding to the dominant eigenvector is always greater than or equal to P_2

10   corresponding to the other eigen channel. The quantizer for the power distribution

11   vector is given in Table 1. Note that we set $P_2 = k\,P_1$, where $0 \le k \le 1$, with $P_1 \ge 0.5P$

12   , where 2 bits are used to describe k.

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14

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Table 1: Quantizer used for the power allocation vector in the case of 4 transmit
antennas and 2 receive antennas.

Water-filling solution	k
$0.75 \leq \frac{P_2}{P_1} \leq 1$	1
$0.5 \leq \frac{P_2}{P_1} \leq 0.75$	$\frac{1}{2}$
$0.25 \leq \frac{P_2}{P_1} \leq 0.5$	$\frac{1}{5}$
$0 \leq \frac{P_2}{P_1} \leq 0.25$	0

2

3 The effect of quantizing the power allocation vector to 2 bits as given in Table 1 can

4 be seen in Figure 3 for the case of 4 transmit antennas and 2 receive antennas. We

5 assume that the eigenvectors are known perfectly at the transmitter for this

6 simulation to study the effects of quantization of the power allocation vector. Figure

7 3 shows the result of a two bit quantizer configured with perfect channel

8 information. It can readily be seen that the two curves are essentially identical, so

9 that the performance loss of the 2 bit power quantizer is negligible compared to the

10 case of perfect channel state information.

11

12 We will now discuss the quantization of the two active eigenvectors of $H^\dagger H$.

13 Consider a finite size beamformer codebook $\mathcal{C}$ of size N constructed as described in

14 the previous section. We can first apply the quantization rule introduced in the last

15 section to determine the best approximation to the dominant eigenvector among the

1   available vectors in $\mathcal{C}$. Note that the specification of this vector at the transmitter

2   requires $\log_2(N)$ feedback bits. However, we can gain substantially in the

3   specification of the second eigenvector by noting the following useful property.

4   Note that the eigenvectors of $H^{\dagger}H$ lie in $\mathbb{C}^t$. Further, the eigenvectors are all

5   mutually orthogonal. Hence, the specification of the first eigenvector determines the

6   subspace which contains the second active eigenvector. In particular, the second

7   eigenvector lies in the t-1 dimensional subspace which is orthogonal to the principal

8   eigenvector. Hence, we can improve the description of the second vector

9   significantly by constructing a second codebook in t-1 dimensions instead of the

10   original t dimensional space.

11   However, it is not desirable to modify the composition of the codebook of the second

12   eigenvector based on the first eigenvector, since the orthogonal subspace containing

13   the second vector depends on the principal eigenvector. We therefore present an

14   algorithm where both the beamformer codebooks are independent of the actual

15   channel realization.

16

17   Let C_1 be a beamformer codebook in $\mathbb{C}^t$ comprising of $N_1=2^{B_1}$ vectors. Similarly, let

18   C_2 be a beamformer codebook in $\mathbb{C}^{t-1}$ comprising of $N_2=2^{B_2}$ vectors. Let H be the

19   channel realization, while V_1 and V_2 are the active eigenvectors of $H^{\dagger}H$.

20   We first quantize V_1 in C_1 using the quantization rule discussed in the last section. In

21   particular, we pick $C_1^i \in C_1$ (note that the superscript corresponds to the codebook

22   index) such that $\left\| H(C_1^i)^{\dagger} \right\|_2$ is the maximum for all the vectors in C_1. Without loss of

23   generality, we assume that C_1^d maximizes the inner product with H among all the

24   vectors in C_1.

25   Now, consider the vectors in C_2. We construct a codebook C_2' from C_2 such that C_2'

26   lies in $\mathbb{C}^t$. Hence, C_2 is an embedding of C_2' in $\mathbb{C}^{t-1}$. By construction, C_2' is such

27   that the first co-ordinate of all the vectors is set to zero. Hence, the vectors in C_2' lie

1 in the orthogonal subspace of the axis $[1, 0, .., 0]$ of $\mathbb{C}^t$. Further, the embedding rule

2 of C_2' into C_2 is that the first co-ordinate of C_2' is dropped to obtain the

3 corresponding vector in C_2. Hence, if $C_i'^2 = [0, c_1, c_2, ...c_{t-1}]$, then the corresponding C_i^2

4 in C_2 is given by $[c_1, c_2, ..c_{t-1}]$.

5 Now, we make use of the property that C_2' is in the orthogonal subspace of

6 $e_1 = [1, 0, ...0]$ in $\mathbb{C}^t$. In particular, we rotate the vectors in C_1 such that C_1^1 coincides

7 with e_1. Let A be a t x t unitary matrix, constructed in a predetermined fashion from

8 C_1^1 such that $AC_1^1 = e_1$. Now, we rotate the channel matrix H by the same matrix A

9 before we quantize the second vector. Equivalently, we rotate the second vector V_2

10 by the matrix A to give $V_2' = AV_2$. Now, we quantize V_2' in the second beamformer

11 codebook $C_2'^2$. Suppose $C_k^{2'}$ is the vector in $C_2^{2'}$ which maximizes the inner product

12 with V_2'. Then, the transmitter gets the label k and the transmitter uses $A(C_k')^T$ for

13 transmission, where the superscript T stands for matrix transpose operation. Note

14 that A is a function of C_1^1 only and since the transmitter has information about C_1^1

15 via the feedback channel, the matrix A can be reproduced at the transmitter. Hence,

16 both the resulting codebooks, C_1 and C_2 are independent of the actual channel

17 realization.

18

Table 2: Table showing the decoding complexity as a function of the number of transmit antennas (t), receive antennas (r) and number of points in the modulation constellation (|Q|).

Transmission scheme	Decoding complexity
Space time coding	$\propto r\lvert Q\rvert^t$
Unit rank beamforming	$\propto r\lvert Q\rvert$
Spatial water-filling	$\propto r\lvert Q\rvert^{\min(t,r)}$

12

1

2   Note that the quantized spatial water-filling solution requires joint coding and

3   decoding across the active eigen channels. Hence, in the case of four transmit and

4   two receive antennas which results in two active eigen channels, we will need joint

5   coding across the two eigen channels. For instance, space time coding of rank 2

6   could be used to achieve the performance depicted in the next section. In the absence

7   of channel state information, we would require a space time code of rank 4

8   corresponding to the four transmit antennas. Note that the decoding complexity of

9   space time codes is exponential in the rank of the code. Hence, the quantized spatial

10   water-filling solution results in significantly lower decoding complexity compared to

11   the space-time coding, in addition to the benefits obtained in performance gains. The

12   dependence of the decoding complexity on the number of transmit antennas and the

13   number of receive antennas is shown in Table 2.

14   The performance of the quantized water-filling solution with 4 transmit antennas and

15   2 receive antennas is given in Figure 3. The figure shows the performance of a

16   quantized water-filling scheme in comparison with the perfect information water-

17   filling scheme, space time coding and perfect information eigenvector beamforming,

18   all transmitting at the rate of $R=6$ bits/sec/Hz. For the quantized beamforming

19   scheme, we have used 2 bits for spatial power control information, using the

20   quantizer given in table 1. We observe the performances of two different codebook

21   constructions in Figure 3. In the first case, the codebook C_1 was constructed in 4

22   dimensions with 16 vectors while the codebook C_2 was constructed in 3 dimensions

23   with 16 vectors, thus requiring 3 feedback bits for each codebook. Hence, a total of

24   10 bits of feedback was used for this scheme. With 10 feedback bits, we note that we

25   are just about 1 dB away from perfect feedback information while we obtain a gain

26   of about 2 dB over space time coding. For the case of 8 feedback bits, we use 2 bits

27   for spatial power control. Again, C_1 is in 4 dimensions, now with 8 vectors, while C_2

28   is in 3 dimensions with 8 vectors, thus requiring 3 bits each. With 8 feedback bits,

13

1   we observe a gain of about 1.5 dB over the space time coding scheme. It should also

2   be pointed out that the unit rank beamforming scheme performs worse than the space

3   time code in this case.

4

5   The beamforming schemes for multiple transmit and receive antenna systems

6   presented above apply when only partial channel state information is available at the

7   transmitter. The unit rank beamforming solution results in a low complexity

8   decoding structures as well as performance gains over channel agnostic space time

9   coding schemes. An algorithm for implementing higher rank transmission schemes,

10   such as a spatial water-filling solution, using low complexity quantizers has also

11   been illustrated. In all the cases, a few bits of channel state information at the

12   transmitter can lead to substantial performance gains as well as reduction in

13   decoding complexity.

14

15   In the next-section, we will show that the design of good beamformers for a multiple

16   transmit and a single receiver system can be posed as the design of unitary space

17   time constellations. The design of the unitary space time constellation is a dual

18   problem of the design of good beamformers with the coherence time in the case of

19   the unitary space time constellation given by the number of transmit antennas in the

20   case of the beamformer design problem. Also, the number of transmit antennas in the

21   equivalent unitary space time constellation design problem is set to unity (which is

22   the number of receive antennas for the beamforming problem). We will establish the

23   equivalence in the sequel and demonstrate the hitherto unknown use of unitary space

24   time constellation as a beamformer with the help of an example. We will use the

25   lower bound outage performance of beamformers for evaluating the performance of

26   the unitary space time constellation as a beamformer.

27

28   Unitary space time constellations for multiple antenna systems were introduced by

29   Marzetta and Hochwald in "Capacity of a mobile multiple-antenna communication

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1   link in rayleigh flat fading", IEEE Transactions on Information Theory, pp 139 –

2   157, January, 1999. In particular, they showed that the unitary space time

3   constellations achieve the capacity of multiple antenna systems when the channel

4   information is not available at both the transmitter and the receiver. The design

5   criterion for unitary space time constellations to minimize the probability of pair-

6   wise error probability was given in "Unitary space-time modulation for multiple-

7   antenna communications in rayleigh flat fading", IEEE Transactions on Information

8   Theory, vol 46, pp. 543-564, March 2000. A unitary space time constellation consists

9   of signals

10    $V_1, V_2, V_3, \ldots V_N$ where $V_i \in \mathbf{C}^{T \times M}$. Here T is the block length of the code (less than or

11   equal to the coherence time of the channel) and M has the interpretation of number

12   of transmit antennas. Also, $V_i^\dagger V_i = I$ for each i, for unitarity. It was shown that the

13   design criterion for good unitary space time constellations is to minimize δ, where

14   δ is defined as

$$\delta \quad = \quad \max_{1 \leq i < i' \leq N} \|\Phi_i^\dagger \Phi_{i'}\|, \tag{1}$$

15

16   where the norm used above is a scaled Frobenius norm of a matrix, the scaling factor

17   being given by M in this case.

18

19   Now consider the design of a good beamformer comprising N vectors for a system

20   with n transmit antennas and a single receive antenna. It can be shown that the

21   design criterion for good beamformers is

22

$$\min_C \quad \max_{1 \leq i < i' \leq N} |\langle C_i, C_{i'} \rangle|, \tag{2}$$

23

24

1   where $C_i \in \mathbb{C}^N$. The design criterion for unitary space time constellations given in

2   (1) reduces to the design criterion of beamformers given in (2), if we set T=m and

3   M=1 in (1). We see an equivalence between coherence time, in the unitary

4   constellation design problem, and the number of transmit antennas, in the

5   beamforming design problem.

6

7   Systematic unitary space time constellation as beamformer

8   The design criterion for beamformers which was introduced in the previous section

9   is quite general and an exhaustive computer search can be used to construct a good

10   beamformer containing a given number of beamforming vectors. We now look at a

11   particular way of designing these beamformers, viz., using a Fourier based approach

12   for unitary space time constellations. Hochwald et al. in "Systematic design of

13   unitary space-time constellations" IEEE Transactions on Information Theory, vol.

14   46, pp. 1962-1973, September 2000, considered the problem of imposing structure

15   on the unitary space time constellations for easier encoding/decoding as well as to

16   reduce the dimensionality of the search space during the design process. The

17   equivalence of good beamformers with good unitary space time constellations

18   established in the previous section reveals the hitherto unknown properties of the

19   systematic constructions. We will show that the unitary space time constellations

20   designed by Hochwald et al. The cited reference serve as good beamformers for the

21   dual problem with the new meaning of the number of transmit antennas attached to

22   coherence time as discussed above.

23   Consider the set of linear block codes defined by the K x T generator matrix U,

24   whose elements are in R_q, ring of integers modulo-q. The code $\mathcal{C}$ represented by U

25   comprises codewords C_i given by $C_i = lU$, where l is a 1 x K vector with elements

26   taken from R_q. Thus, the size of the codebook is given by $|\delta| = q^K$. The codewords

27   are mapped into signals by mapping the integers in the codeword into components of

28   a complex signal via the transformation

$$\phi(j) \quad = \quad \frac{1}{\sqrt{T}} e^{i\frac{2\pi}{q}j}, j = 0, 1, ..q - 1. \tag{3}$$

Finally, the unitary space time constellation is given by

$$\Phi_l \quad = \quad \phi(C_l) \tag{4}$$

$$= \quad \frac{1}{\sqrt{T}} \begin{bmatrix} e^{i\frac{2\pi}{q}[C_l]_1} \\ e^{i\frac{2\pi}{q}[C_l]_2} \\ \cdot \\ \cdot \\ e^{i\frac{2\pi}{q}[C_l]_T} \end{bmatrix}, 1 \leq l \leq N$$

Suppose, we wish to design a beamformer comprising of N=16 vectors for n=8 transmit antennas transmitting at 2 bits/sec/Hz and a single receive antenna. Then the corresponding dual problem of designing unitary space time constellation reduces to designing a codebook of size N=16 with a single transmit antenna (i.e., M=1) and coherence time given by T=8. One of the codes designed for this problem in the cited reference is characterized by U=[1 0 3 14 15 11 10 8], K=1 and q=16.

The performance of this beamformer is given in Figure 5. The rate of transmission is R=2bits/sec/Hz. The corresponding performance predicted by the lower bound on outage is also given in the figure. It can be seen that the performance of the constructed beamformer comes very close (less than 0.05dB away) to the corresponding lower bound on outage probability. The performance of space time codes, which do not require any feedback information, is also given in the plots for reference. Note that there is gain of about 4dB with 4 bits of feedback compared to the space time codes. It should also be noted that there will be gains from reduced

17

1 receiver complexity also from the beamforming schemes which are not quantified in

2 this document.

3 A similar construction taken from the cited reference again for n=8 transmit antennas

4 and N=64 beamforming vectors is given in Figure 6. The unitary space time

5 constellation in this case is characterized by N=64, T=8, K=3, q=4 and U = [I_3 U'],

6 where I_3 is the 3x 3 identity matrix and U' is given by

$$U' = \begin{bmatrix} 2 & 3 & 3 & 3 & 0 \\ 2 & 0 & 3 & 1 & 1 \\ 0 & 3 & 2 & 3 & 3 \end{bmatrix} \tag{5}$$

7

8

9 For the case of 64 beamforming vectors, we present another straight-forward

10 beamforming scheme for comparison. We use 1 bit to quantize the phase information

11 of each one of the channel coefficients, leading to 8 bits in all, for 8 channel

12 coefficients. The performance of this beamformer is also plotted in Figure 6. It can

13 be seen that the performance of the constructed beamformer is again less than

14 0.05dB away from the corresponding bound . Further, the gain compared to the

15 space time coding scheme now increases to about 6 dB. It can be observed from the

16 plot there is lot of gain compared to the phase quantization scheme also. This shows

17 that the systematic unitary space time constellations serve as very good

18 beamformers. Some more constructions of the beamformers for n=8 transmit

19 antennas can be obtained from the cited reference for the cases of N=133, 256, 529,

20 1296 and 2209 vectors.

WE CLAIM:

1   1.   A method of forming a beam of a signal to be transmitted from a base station transceiver
2   in a communication system having a communication channel between a base station and a
3   mobile station and a return channel for data transmitted from the mobile station to the base
4   station, the method comprising:
5
6   Providing a codebook (C) of parameters that modify a transmitted signal:
7   Providing a channel matrix (H) of parameters representing the properties of the channel;
8   transmitting a signal from the base station along a channel using an antenna comprising at
9   least two elements;
10 Receiving said transmitted signal in said mobile station and estimating a parameter in the
11 channel matrix characteristic of the channel by selecting the value of a parameter in the
12 codebook that minimizes a criterion;
13 transmitting an indication of the selected parameter over the return channel and
14 applying the codebook vector associated with the selected parameter to subsequent transmissions
15 from the base station.

1   2.   A method according to claim 1, in which an eigenvector of said channel matrix is
2   provided by a calculation based on said parameter.

1   3.   A method according to claim 2, in which said calculation is performed in said mobile
2   station.

1   4.   A method according to claim 1, in which said base station transmits a set of initial setup
2   signals that are used by the mobile station to estimate the parameters of the channel.

1   5.   A method according to claim 4, in which an eigenvector of said channel matrix is
2   provided by a calculation based on said parameter.

1   6.   A method according to claim 5, in which said calculation is performed in said mobile
2   station.

1   7.   A method according to claim 1, in which the signal is divided into frames and the process
2   of estimating a parameter, transmitting an indication of the selected parameter and applying the
3   codebook vector is repeated for each frame.

1   8.   A method according to claim 7, in which an eigenvector of said channel matrix is
2   provided by a calculation based on said parameter.

1   9.   A method according to claim 8, in which said calculation is performed in said mobile
2   station.

1   10.   A method according to claim 1, in which said base station transmits a set of initial setup
2 signals that are used by the mobile station to estimate the parameters of the channel.

1   11.   A method according to claim 10, in which an eigenvector of said channel matrix is
2 provided by a calculation based on said parameter.

1   12.   A method according to claim 11, in which said calculation is performed in said mobile
2 station.

1   13.   A method of forming a beam of a signal to be transmitted from a base station transceiver
2 in a communication system having a communication channel between a base station and a
3 mobile station having two antennas and a return channel for data transmitted from the mobile
4 station to the base station, the method comprising:
5
6 Providing a codebook (C) of parameters that modify a transmitted signal;
7 Providing a channel matrix (H) of parameters representing the properties of the channel;
8   transmitting a signal from the base station along two eigenvectors of a channel, the power
9   allocation between said two eigenvectors being quantized independently from the
0   quantization of the eigenvectors.

1   14.   A method according to claim 13, in which the quantization of the power allocation is
2 performed at the receiver.

1   15.   A method according to claim 13, in which $P_1 = kP_2$, where $0 \leq k \leq 1$, P_1 is
2 the power in the dominant eigenvector and k is selected from the group comprising 1, ⅓, 1/5, and
3 0 when $R = \dfrac{P_2}{P_1}$ is correspondingly ≥ 0.75, $0.5 < R < 0.75$, $.25 < R < 0.5$ and $0 < R < .25$. .

1   16.   A method according to claim 13, in which the dominant eigenvector is quantized by
2 calculating the eigenvector in the relevant codebook that maximizes $\left\| H(C_i^1)^1 \right\|_2$.

1   17.   A method according to claim 16, in which the second of two eigenvectors is calculated by
2 finding that vector in an orthogonal subspace to the first eigenvector that maximizes the inner
3 product with a beamformer codebook in the orthogonal subspace to the first codebook.

1   18.   A method according to claim 16, in which the quantization of the power allocation is
2 performed at the receiver.

1   19.   A method according to claim 16, in which which $P_1 = kP_2$, where $0 \leq k \leq 1$, P_1 is
2 the power in the dominant eigenvector and k is selected from the group comprising 1, ⅓, 1/5, and
3 0 when $R = \dfrac{P_2}{P_1}$ is correspondingly ≥ 0.75, $0.5 < R < 0.75$, $.25 < R < 0.5$ and $0 < R < .25$. .

1 20.   A method of constructing a beamformer comprising the steps of:
2   Providing a unitary space-time constellation of at least one signal ₁ having a coherence time T
3   and one transmit antenna and applying the constellation as a set of at least one beamforming
4   vectors in an array of T antennas.

1 21.   A method according to claim 20, in which said set of at least one functions have the form
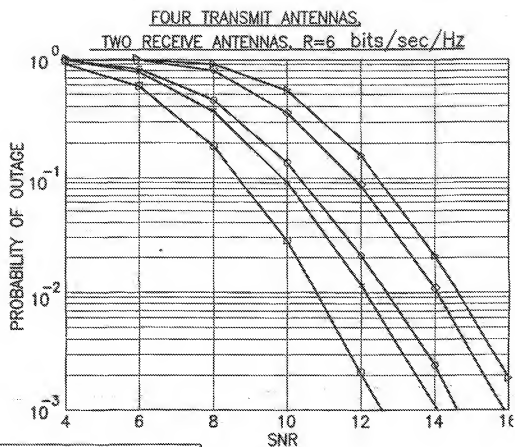
2      $V_i = \frac{1}{\sqrt{T}} \exp(\frac{i 2\pi j}{N})$ where $j = 0,1,2...N-1$ ..

1 22.   A method of constructing a beamformer of N vectors comprising the steps of:
2   Providing a transmitter system having n transmit antennas;
3   Forming a set of N functions in a unitary space time constellation with one antenna and a
4   coherence time of n; and
5   Applying said set of N functions as a set of N beamforming vectors.

1 23.   A method according to claim 22, in which said set of N functions have the form

2      $V_i = \frac{1}{\sqrt{n}} \exp(\frac{i 2\pi j}{N})$ where $j = 0,1,2...N-1$ ..

21

1 24. A method according to claim 20, of forming a beam of a signal to be transmitted
2 from a base station transceiver in a communication system having a communication
3 channel between a base station and a mobile station and a return channel for data
4 transmitted from the mobile station to the base station, the method comprising:
5
6 Providing a codebook (C) of parameters that modify a transmitted signal according to
7 claim 20;
8 Providing a channel matrix (H) of parameters representing the properties of the channel;
9   transmitting a signal from the base station along a channel using an antenna
10   comprising at least two elements;
11 Receiving said transmitted signal in said mobile station and estimating a parameter in the
12 channel matrix characteristic of the channel by selecting the value of a parameter in the
13 codebook that minimizes a criterion; transmitting an indication of the selected parameter
14 over the return channel and
15 applying the codebook vector associated with the selected parameter to subsequent
16 transmissions from the base station.
17
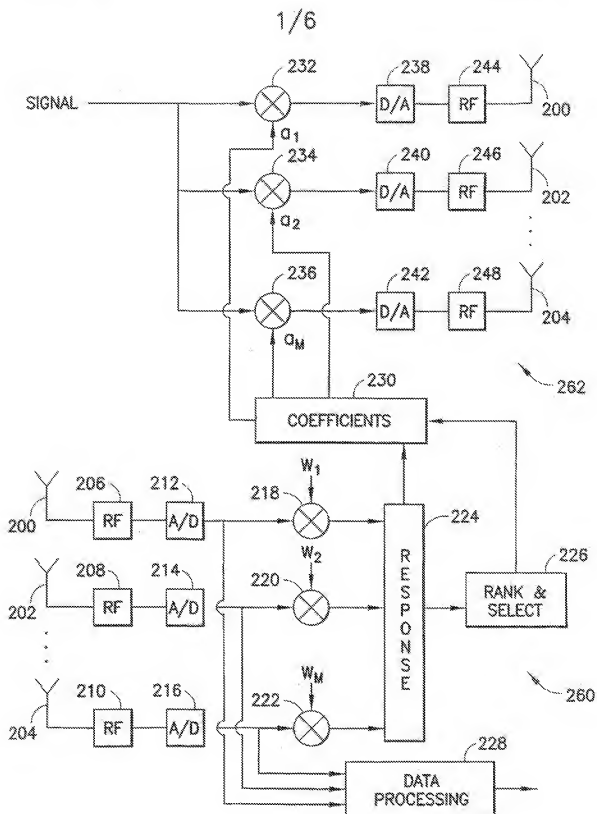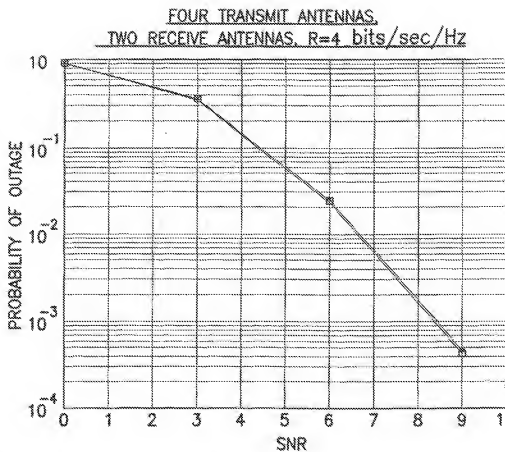
FIG.1

FOUR TRANSMIT ANTENNAS,
TWO RECEIVE ANTENNAS, R=2 bits/sec/Hz

FIG.2

FOUR TRANSMIT ANTENNAS,
TWO RECEIVE ANTENNAS, R=4 bits/sec/Hz

PROBABILITY OF OUTAGE

SNR

FIG.3

SPATIAL WATER-FILLING WITH PERFECT CSIT
POWER ALLOCATION QUANTIZED TO 2 BITS

FIG.4

FOUR TRANSMIT ANTENNAS,
TWO RECEIVE ANTENNAS, R=6 bits/sec/Hz

PROBABILITY OF OUTAGE

SNR

- WATER-FILLING
- QUANTIZED WATER-FILLING 10 FEEDBACK BITS
- QUANTIZED WATER-FILLING 8 FEEDBACK BITS
- SPACE TIME CODING
- DOMINANT EIGENVECTOR

FIG.5
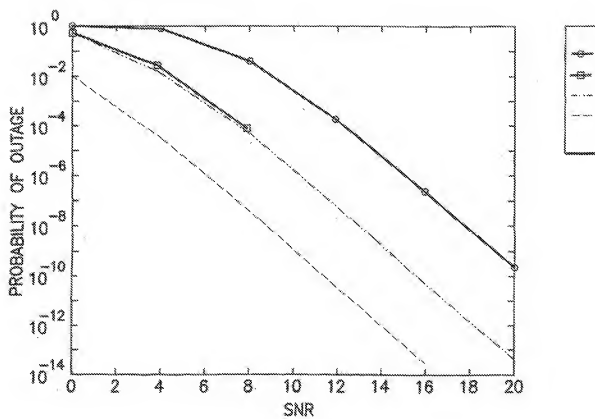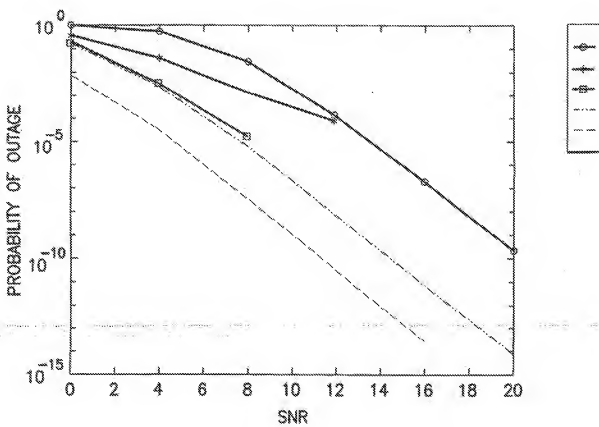
FIG.6

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H04B 7/14, 1/02, 7/02
US CL : 455/561, 25, 101, 103, 70, 130, 137; 375/316, 349
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 455/561, 25, 101, 103, 70, 130, 137; 375/316, 349

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 2003/0185309 A1 (PAUTLER et al) 02 October 2003, see entire document.	1-14 and 24
A	US 2002/0013139 A1 (KIM et al) 31 January 2002, see entire document.	1-24
A,P	US 2004/0033791 A1 (SCHMIDL et al) 19 February 2004, see entire document.	1-24
A,P	US 2003/0181170 A1 (SIM) 25 September 2003, see entire document.	1-24
A	US 5,933,457 A (HOTTINEN) 03 August 1999, see entire document.	1-24

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
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"L" document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 April 2004 (27.04.2004)	20 MAY 2004
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (703) 305-3230	Authorized officer John Orgad Telephone No. 703-305-4223

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